

# $^{26}\text{Al}$ sources in the Galaxy as seen in the 1.809 MeV gamma-ray line

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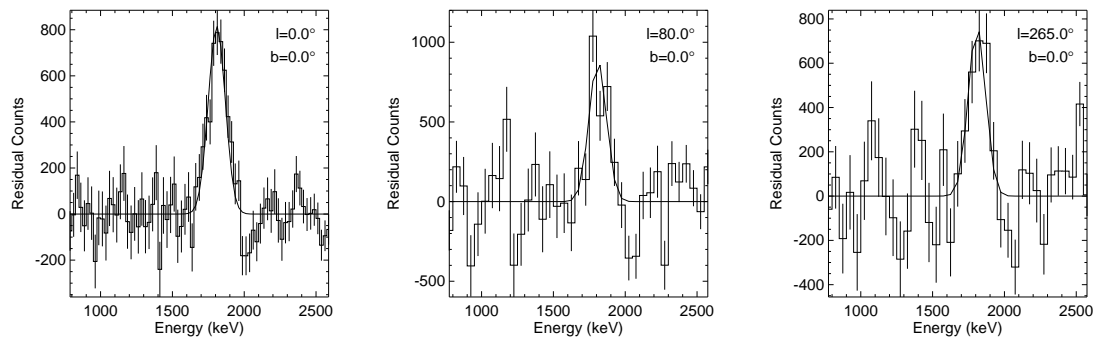
**Abstract.** Gamma-ray line observations provide a versatile tool for studies of nucleosynthesis processes and supernova physics. In particular, the observation of radioactive species in the interstellar medium probes recent nucleosynthesis activity on various time-scales for different kinds of sources. Considerable progress in gamma-ray instrumentation during the last decades has led to the discovery of several cosmic gamma-ray lines. The best studied of these lines is today the 1.809 MeV line attributed to the decay of radioactive  $^{26}\text{Al}$  within the interstellar medium. In this review, recent observational results are presented and their astrophysical implications are discussed.

## INTRODUCTION

Convincing proof of ongoing nucleosynthesis in the Galaxy comes from the observation of the 1.809 MeV gamma-ray line, emitted during the radioactive decay of  $^{26}\text{Al}$ . With a lifetime of  $10^6$  yr, much shorter than the timescale of galactic evolution,  $^{26}\text{Al}$  must have been freshly synthesised to be observable in the interstellar medium today. In principle,  $^{26}\text{Al}$  could be produced in appreciable amounts by a variety of sources, such as massive mass losing stars (mainly during the Wolf-Rayet phase), Asymptotic Giant Branch stars (AGBs), novae (mainly of ONe subtype), and core collapse supernovae. In addition to stellar production,  $^{26}\text{Al}$  can also be produced by spallation reactions of high-energy cosmic rays, although at substantially lower rates (see [22] for a recent review).

Considerable uncertainties that are involved in the modelling of nucleosynthesis processes, mainly due to the poorly known physics of stellar convection, do not allow for a theoretical determination of the dominant galactic  $^{26}\text{Al}$  sources. In view of this difficulty, it has been suggested that help could be expected from a combination of improved spatial source distribution models and observations with good angular resolution [16]. However, until recently, the angular resolution and sensitivity of gamma-ray detectors were too poor to perform such a mapping; hence the origin of galactic  $^{26}\text{Al}$  remained veiled.

The situation changed dramatically after the launch of the Compton Gamma-Ray Observatory (*CGRO*), in April 1991. The COMPTEL telescope aboard *CGRO*



**FIGURE 1.** Background subtracted COMPTEL count spectra of the galactic centre (left), the Cygnus region (middle), and the Vela region (right). 1.809 MeV gamma-ray line signatures are clearly visible in all spectra.

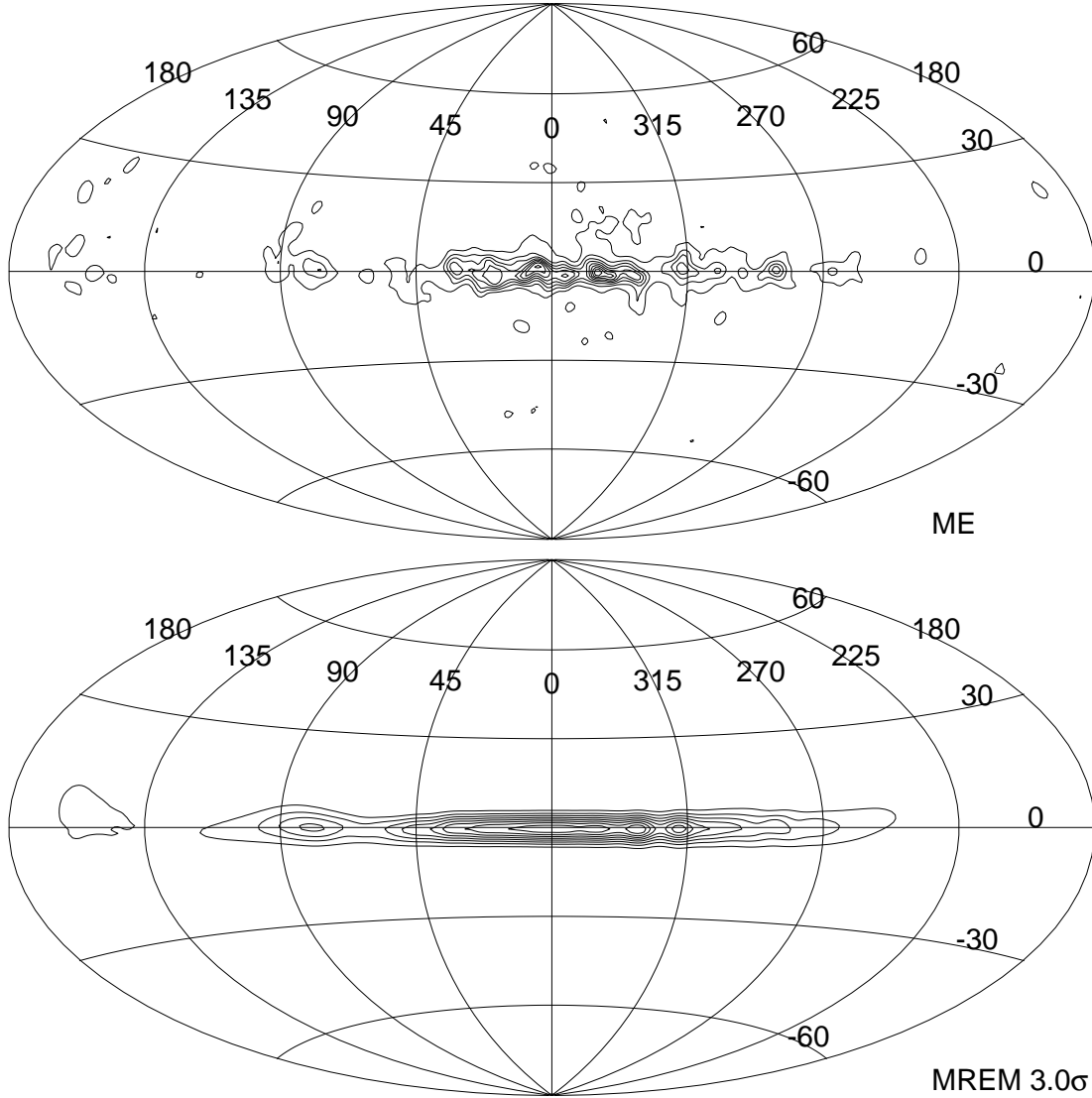
performed the first mapping of the Galaxy in the light of 1.809 MeV photons [3]. I will review these observations in this paper, and summarise what has been learned about the origin of  $^{26}\text{Al}$ .

## OBSERVATIONS

The COMPTEL telescope allows the study of 1.8 MeV gamma-ray line emission with an energy resolution of  $\sim 8\%$  (FWHM) and an angular resolution of  $3.8^\circ$  (FWHM) within a wide field of view of about 1 steradian [23]. Combination of observation periods of typically 1-2 weeks allows to extend the field of view to the entire sky, enabling an all-sky analysis of cosmic 1.8 MeV line emission. Using data from the first five years of the *CGRO* mission led to a point source sensitivity of  $1 \cdot 10^{-5} \text{ ph cm}^{-2} \text{ s}^{-1}$  ( $3\sigma$ ), a performance that exceeds by far the limits of precedent telescopes. Hence for the first time, galactic 1.8 MeV gamma-ray line emission could be studied in great detail.

For illustration, background subtracted COMPTEL count spectra for three regions along the galactic plane are shown in Fig. 1 [8]. The first panel shows the well known 1.8 MeV line from the galactic centre region which has been detected by numerous instruments [22], but never at such high significance. 1.8 MeV line emission from Cygnus and Vela, as seen in the next two panels, has never been reported before. Both regions are roughly  $90^\circ$  away from the galactic centre, illustrating that  $^{26}\text{Al}$  production is not only concentrated on the galactic centre. In fact, from the relative intensities with respect to the galactic centre emission it becomes clear that the galactic  $^{26}\text{Al}$  distribution obeys a rather flat profile along the galactic plane, inconsistent with proposed distributions for novae that are highly peaked towards the galactic centre.

COMPTEL images of 1.8 MeV gamma-ray line emission are obtained by deconvolving the data in a narrow energy band centred on the line energy. This procedure relies on accurate modelling of the instrumental background which is



**FIGURE 2.** COMPTEL 1.8 MeV all-sky maps derived using a maximum entropy algorithm (top) and the multi-resolution algorithm MREM (bottom).

obtained by interpolating observations at adjacent energies, thus removing possible contributions from continuum sources [6]. A maximum entropy (ME) all-sky image of 1.8 MeV line emission is shown in Fig. 2 in Aitoff-projection [21]. The image reveals lumpy emission structures along the galactic plane with ‘hot spots’ eventually separated by emission-free ‘gaps’. Some degree of lumpiness in the 1.809 MeV emission is expected if massive stars are at the origin of galactic  $^{26}\text{Al}$ , since they mainly form in stellar associations which are probably aligned along the spiral arm structure of the Galaxy. Indeed, the comparison of the data to detailed models of galactic spiral structure supports such a correlation [7]. However, the amount of emission lumpiness seen in the ME image even exceeds expectations for massive

star associations [17], questioning the origin of the image lumpiness.

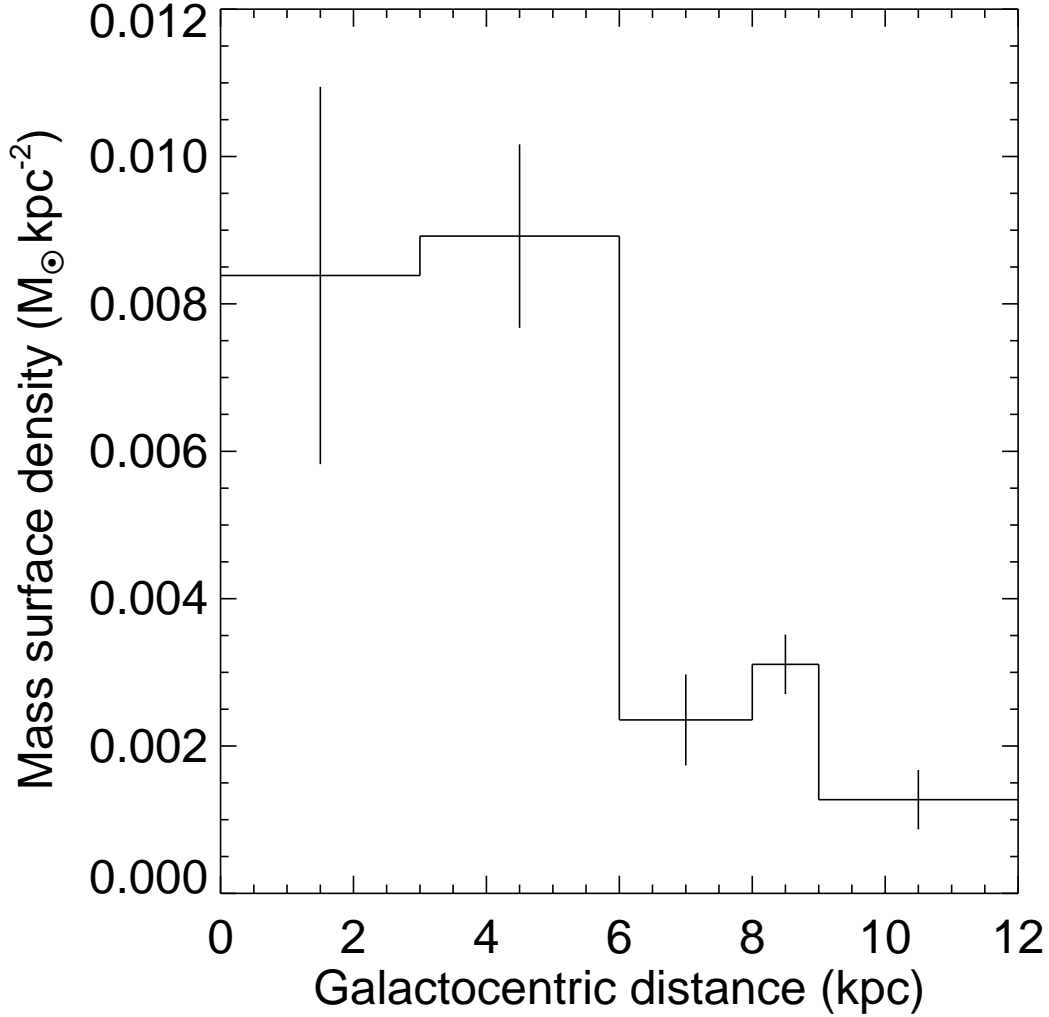
It has gradually become clear that at least part of the image lumpiness is an artifact of the image reconstruction process [6]. It results from the weak constraints that are imposed on individual image pixels by our data, leading to a propagation of statistical noise into the deconvolved skymaps. We therefore developed a new algorithm, called MREM, that we specifically designed for the reconstruction of diffuse, low-level gamma-ray emission [12]. Application of the MREM algorithm to COMPTEL data leads to an alternative image of 1.809 MeV gamma-ray line emission that reveals much less image lumpiness (cf. Fig. 2). We believe that most emission structures that are seen in the MREM image are indeed real. However, we cannot exclude that weak emission structures that are close to the sensitivity limit of COMPTEL have been smoothed out by the MREM reconstruction process.

Despite the different amounts of image lumpiness in the two reconstructions, both skymaps have features in common. The maps reveal an intense, asymmetric ridge of diffuse 1.809 MeV emission along the galactic plane with a prominent localised emission enhancement in the Cygnus region. The longitude profile of the emission is rather flat and does not show any pronounced emission enhancement towards the galactic centre. This clearly illustrates that  $^{26}\text{Al}$  nucleosynthesis is not localised to specific areas of our Galaxy, such as the galactic centre or the local interstellar medium [5,20]. It is a galaxywide phenomenon which reflects the recent nucleosynthesis activity throughout the Milky Way.

The emission enhancement in Cygnus is of particular interest. By searching for possible counterparts of the emission, it turned out that the observations can be explained by the combined nucleosynthesis activity of Wolf-Rayet stars and core collapse supernova in a group of OB associations and young open clusters situated at 1-2 kpc from the Sun [2]. Hence, the Cygnus feature is a fingerprint of recent nucleosynthesis activity in the local interstellar medium, probably related to the local spiral arm structure. In this picture, the 1.8 MeV emission seen towards Vela could represent the continuation of the local spiral arm at negative longitudes after passing near the Sun [9].

In our continuous effort in finding tracers of recent nucleosynthesis activity [3,4] we recently discovered two intensity distributions that are closely correlated to 1.809 MeV emission: galactic free-free emission, observed by the DMR telescope aboard *COBE* in the microwave domain, and the 158  $\mu\text{m}$  fine-structure line of  $\text{C}^+$ , observed by FIRAS (also aboard *COBE*) [11,13]. Both distributions are tracers of the ionised interstellar medium, hence they directly reflect the galactic population of very massive ( $M_i > 20 M_\odot$ ) stars [10]. The observed correlations suggest that  $^{26}\text{Al}$  is primarily produced by the same population. Consequently, due to the short lifetime of massive stars,  $^{26}\text{Al}$  becomes an excellent tracer of recent galactic star formation.

From the correlations I inferred an equivalent O7V star  $^{26}\text{Al}$  yield of  $Y_{26}^{\text{O7V}} = (1.0 \pm 0.3) 10^{-4} M_\odot$ , expressing the amount of  $^{26}\text{Al}$  produced by a typical massive, ionising star. Remarkably, this value is in good agreement with yield estimates for massive Wolf-Rayet stars [15,18]. Using an estimate of the galactic Lyc luminosity



**FIGURE 3.**  $^{26}\text{Al}$  mass surface density as derived from COMPTEL 1.8 MeV gamma-ray line data.

of  $Q = 3.5 \cdot 10^{53} \text{ ph s}^{-1}$  [1], the equivalent O7V star  $^{26}\text{Al}$  yield converts into a galactic  $^{26}\text{Al}$  mass of  $3.1 \pm 0.9 M_{\odot}$ . This value is to be compared to nucleosynthesis predictions of  $2.2 \pm 0.4 M_{\odot}$ , where  $\sim 60\%$  of the galactic  $^{26}\text{Al}$  is predicted to arise from Wolf-Rayet stars while  $\sim 40\%$  should come from core collapse supernovae [10].

We can now use  $^{26}\text{Al}$  to learn more about massive star formation in the Galaxy by observations of the 1.809 MeV gamma-ray line. For example, using a maximum likelihood procedure, we can derive the radial  $^{26}\text{Al}$  mass density distribution in the Galaxy, which in turn reflects the radial dependence of the star formation rate. The resulting profile is shown in Fig. 3 [8]. The data illustrate that the bulk of galactic star formation occurs at distances of less than 6 kpc from the galactic centre.

Star formation is also present within the central 3 kpc of the Galaxy, although at a poorly determined rate. There are indications for enhanced star formation between 3 – 6 kpc, coinciding with the molecular ring structure as seen in CO data. Enhanced star formation is also seen in the solar neighbourhood (8 – 9 kpc) which probably corresponds to the local spiral arm structure. However, the radial  $^{26}\text{Al}$  profile is probably not directly proportional to the radial star formation profile since  $^{26}\text{Al}$  nucleosynthesis may depend on metallicity. It will be important to determine this metallicity dependence in order to extract the true star formation profile from gamma-ray line data. Valuable information about the metallicity dependence will come from a precise comparison of the 1.809 MeV longitude profile to the profile of free-free emission. Additionally, observations of gamma-ray lines from  $^{60}\text{Fe}$ , an isotope that is only believed to be produced during supernova explosions, can help to distinguish between hydrostatically and explosively produced  $^{26}\text{Al}$ , and therefore help to disentangle the metallicity dependencies for the different candidate sources.

## WHERE DO WE STAND? WHERE DO WE GO?

COMPTEL observations of the 1.809 MeV gamma-ray line mark the beginning of a new epoch in gamma-ray line astronomy. For the first time, the entire Galaxy has been imaged in a gamma-ray line, supplying us with a map of recent nucleosynthesis activity. A connection between nucleosynthesis and massive star formation has been established, linking gamma-ray line astronomy to fields like stellar evolution, galactic evolution, galactic structure, and the physics of the interstellar medium.

COMPTEL observations suggest that massive stars are the primary source of galactic  $^{26}\text{Al}$ , although a small contribution (10-20%) from novae or AGB stars cannot be excluded at this point. The expectations are now focused on SPI, the spectrometer aboard the *INTEGRAL* observatory, scheduled for launch in 2001. SPI not only brings a further improvement in sensitivity and angular resolution, it also combines imaging with high-resolution spectroscopy, a novelty in gamma-ray line astronomy (see <http://astro.estec.esa.nl/SA-general/Projects/Integral/integral.html>). During the core program, which will cover 25 – 35% of the observation time, INTEGRAL will perform a deep survey of the central radian and a weekly scan of the galactic plane. During these surveys, significant exposure will be accumulated along the galactic plane, allowing for a detailed mapping of galactic 1.809 MeV emission. Additionally to the spatial mapping, line shapes will be measured to high precision, enabling to detect line broadenings or shifts of a few 100 km s<sup>-1</sup>. The line shape analysis is of particular importance in light of a possible 1.809 MeV line broadening, suggested by *GRIS* balloon observations of the galactic centre region [19].

The remaining observation time is open to the scientific community, allowing for detailed studies of localised 1.809 MeV emission features. A prime candidate for such studies is, of course, the Cygnus region, where SPI observations could reveal substructures related to different massive star populations. Comparison of these

observations with other tracers of massive star formation, such as galactic free-free emission, and their interpretation using multi-wavelength evolutionary synthesis models, will provide a powerful analysis tool for studies of nucleosynthesis processes in this region [14]. Comparable in interest are probably the Vela and the Carina regions, where hints for localised emission features have been found in COMPTEL data.

Thus, the story about galactic 1.809 MeV is by far not over – it just began. It is not unrealistic that 1.809 MeV line diagnostics will become a standard tool in astrophysics, complementing information obtained at other wavelengths. Stay tuned ...

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